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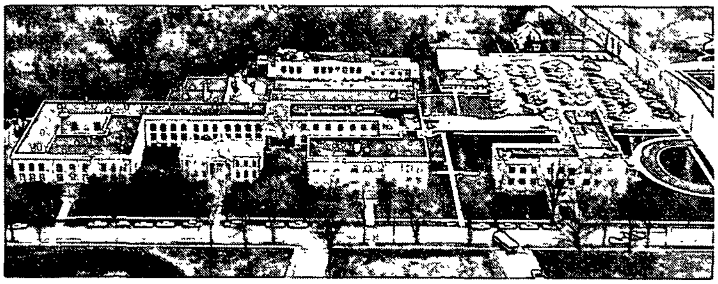

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THE INFLUENCE OF LOW-LIGNIN PULPING CONDITIONS ON BLEACHABILITY: THE EFFECTS OF ANTHRAQUINONE AND EFFECTIVE ALKALI CHARGE

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THE INFLUENCE OF LOW-LIGNIN PULPING CONDITIONS ON BLEACHABILITY: THE EFFECTS OF ANTHRAQUINONE AND EFFECTIVE ALKALI CHARGE

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ABSTRACT

A multilevel factorial experiment was done to study the relationship between pulping conditions and CED sequence bleachability in the preparation of conventional and low-lignin softwood kraft and kraft anthraquinone (AQ) pulps. A limited charge of ClO_2 was used to exaggerate the effects. In general, bleachability was relatively unaffected by changes in effective alkali (EA) charge, AQ charge and unbleached kappa no. over the ranges studied. Addition of 0.1% AQ to the kraft cook gave slightly lower bleached brightness than either 0 or 0.2%. Permanganate number after the extraction stage decreased with increasing AQ charge and decreasing unbleached kappa no. Reducing the unbleached kappa no. from 35 to 15 by cooking for a longer time in the presence of adequate EA was observed to have no detrimental effects on the ease of residual lignin removal.

INTRODUCTION

Kraft pulping of softwoods to kappa numbers lower than about 30 is generally regarded as undesirable. The reasons for this are the detrimental effects of overcooking on pulp yield and strength properties. It should be remembered, however, that yield and strength are by no means single-valued functions of unbleached lignin content and that lower unbleached kappa numbers offer considerable advantages in the form of reduced bleaching chemical costs and reduced bleachery effluent pollution loadings, especially color.

Thus, lowering unbleached kappa no. from 30 to, e.g., 20, by simply prolonging the cook, will result in yield loss and possibly strength deterioration. On the other hand, if the kappa no. reduction is achieved by making suitable changes in the liquor composition, perhaps in conjunction with a change in the cooking time, these undesirable effects can be avoided.[1-3] Since there are many possible combinations of cooking time, effective alkali (EA), sulfidity, etc., for arriving at a given combination of kappa no., yield and strength, a choice must be made on the basis of other factors. These will include the bleachability of the pulp.

The manner in which bleachability depends on pulping conditions has not been extensively studied. It is the central theme of only one article in the recent literature, that being work of Carno et al.,[4] who studied the influence of EA charge on the bleachability of kraft pulps having kappa numbers in the range 30-40. They found that both unbleached brightness and fully bleached brightness increased with increasing EA charge and that fully bleached brightness increased with increasing unbleached kappa no. The latter phenomenon was attributed to the higher specific light absorption coefficient of the lignin in the lower kappa pulps. In related research, Virkola et al.[12] found a detrimental effect of decreased kappa no. on bleachability when the kappa no. decrease was achieved by increasing the EA charge. Norden and Teder[2] also alluded to a detrimental effect of reduced kappa no. on bleachability, without specifying how the lower kappa numbers were achieved. A further illustration of the importance of pulping conditions was provided by Teder and Tormund in their account of the greater bleachability of the lignin in low-kappa no. polysulfide pulps than in the corresponding kraft pulps.[5] A similar observation was also made by Makkonen.[13]

The advent of anthraquinone (AQ) as a pulping promoter has catalyzed alkaline pulping research, and a number of studies have, at least to some extent, examined its effect on pulp bleachability.[5-9] This is of interest in the present context since AQ addition offers the possibility of pulping to lower kappa no. without incurring yield or viscosity losses. Holton, in his original paper on the subject[6] presented limited data on the comparative CEDED bleaching of black spruce kraft pulps prepared with and without addition of 2-methyl anthraquinone, and concluded that the chemical consumptions were equivalent. Subsequent authors[7-9] are in general agreement that addition of AQ under otherwise more or less standard pulping conditions results in little or no loss in fully bleached brightness. None of these studies, however, has examined the effects of varying the anthraquinone charge in conjunction with other pulping variables, and none has been concerned with effects which may appear when pulping to lower-than-normal kappa no.

The present work was designed to address these questions and to extend preliminary studies of low-lignin pulp bleachability reported on earlier.[1] At that time, it was observed that pulps prepared according to a few different kappa no. minimizing strategies were delignified more easily the lower the unbleached kappa no. Response to chlorine dioxide in the succeeding stages was, however, quite different for the different pulps. Although the differences became smaller as the chlorine dioxide charge was increased, the low-lignin pulps tended to have lower final brightness. It thus became apparent that, for bleachability to become an input into the overall optimization, it would be necessary to gain a better understanding of its relationship to pulping variables.

In the present work, a multilevel factorial experiment was carried out to examine the effects of EA charge, AQ charge, kappa no., and the pairwise interactions of these variables. The raw material was southern yellow pine, and the resulting pulps were bleached under fixed conditions in the CED sequence. In an effort to exaggerate the effects of the pulping conditions, the ClO_2 charge in the D-stage was limited to 0.8%, a value short of the ClO_2 demand of a typical softwood kraft pulp in this

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sequence.

RESULTS AND DISCUSSION

The experimental data are contained in Tables I and II. Analysis of variance and multiple regression analysis were used to separate the general trends in the data from the minor effects and the experimental error variation. The regression equations are listed in Table III and are plotted in Figure 1 together with the appropriate means computed from the individual data points in Tables I and II.

Unless noted otherwise, all curves represent values calculated from the regression equations as a function of kappa no. with one variable as parameter and the other held constant at its average value (19% for EA, 0.0875% for AQ).

Unbleached Pulp Properties

Figures 1 and 2 illustrate the well-known accelerating effects of AQ addition and of increasing the EA charge. AQ reduces the H-factor requirement by larger amounts at lower kappa no. Increasing the EA charge has an effect on the H-factor requirement which is analogous to that of adding AQ.

The effect of AQ on yield was roughly 1% at the 0.1% AQ level as shown in Figure 3. (It is interesting to note that the effects of AQ on both yield and H-factor were linear, showing no tendency to level off with increasing AQ charge over the range studied.) Figure 4 shows that the yield was reduced by 0.5% for each 3% increase in EA charge.

Pulp viscosity, at any given kappa no., was increased by adding AQ and decreased by increasing the EA charge (Figures 5 and 6).

Zero-span tensile strength, corrected to 50% yield, underwent effects qualitatively similar to those on viscosity as is evident from Figures 7 and 8. However, the beneficial effect of AQ on zero-span, unlike that on viscosity, was most pronounced at low kappa no. and tended to disappear at higher kappa no. The negative effect of EA on zero-span, on the other hand, was apparent over the whole range.

The brightness of the unbleached pulp was affected by all three experimental variables as shown in Figures 9 and 10. It increased with decreasing kappa no. and with increasing EA charge, as has been previously observed.[4] In addition, there was a small negative effect of AQ at fixed kappa no., which suggests that AQ addition results in the formation of a darker-colored residual lignin.

In summary, characterization of the unbleached pulps showed that the effects of the experimental variables on H-factor requirement, yield, viscosity, and brightness were qualitatively similar to those observed previously.[1,4] Zero-span tensile strength varied in the directions predicted by the viscosity measurements. However, the increased beneficial effect of AQ as the kappa number was decreased was apparent from the zero-span, but not the viscosity data.

Bleach Response

All of the experimental pulps were subjected to chlorination (C) and caustic extraction (E) stages under a standard set of conditions, which included a fixed ratio of Cl_2 charge to unbleached kappa no. and a fixed ratio of NaOH charge to Cl_2 charge. Subsequently, both the permanganate (K) number and the viscosity of the extracted pulp were measured. As is apparent from Figure 11, the K no. decreased with decreasing unbleached kappa no. and with increasing AQ charge. The effect of AQ was most apparent at the high end of the kappa no. range. EA charge was observed to have no effect on extracted K no.

It thus appears that AQ, presumably by inhibition of lignin condensation and/or bonding to carbohydrate during the cook, renders the residual lignin more easily removable by chlorination and caustic extraction. Increasing the EA charge has no similar effect and accelerates the cook only by providing a greater concentration driving force for the delignification process. The effect of unbleached kappa no. has also been observed by Grangaard,[10] who showed that it is diminished by employing prolonged chlorination stages. This suggests that lignin removal at the higher kappa no. is limited by its accessibility to chlorine as a result of the slow diffusion of chlorolignin from the pulp. As the amount of lignin to be removed is decreased, accessibility becomes less of a problem. A similar explanation has been put forward by Rydholm[11] for the greater ease of residual lignin removal from sulfite than from kraft pulps. In the former diffusion of chlorolignin from the fiber is facilitated by the water solubility imparted by its sulfonic acid groups.

Viscosity loss in the chlorination and extraction stages was generally small, averaging slightly more than 1 cp and was relatively insensitive to pulping conditions. This is illustrated by Figure 12, in which the viscosity after these stages is plotted against unbleached viscosity. There was a slight, but statistically significant, tendency for pulps of intermediate kappa no. and those prepared with higher AQ charges to lose more viscosity.

As mentioned earlier, the method chosen for assessing the response of the chlorinated and extracted pulps to ClO_2 was a standardized single treatment with a limited amount of ClO_2. This procedure was expected to emphasize the differences between pulps by interrupting the brightening process at the point of maximum separation between bleach response curves, since such curves tend to converge at high ClO_2 charges. This method unfortunately also emphasizes the effects of extraneous variables, especially pH, which is difficult to control precisely without advance knowledge of the effects of the experimental variables on ClO_2 demand, acidity, and buffering capacity of the system. For this reason, it was necessary to include pH as an additional independent variable in the analysis of the data.

The correlation between brightness after the ClO_2 stage and the experimental variables was not strong, with much of the variation being attributable to variations in the final pH of the ClO_2 stage itself. There was, however, a significant effect of AQ charge, which is illustrated in Figure 13. As the AQ charge was increased, the brightness first fell and then increased to the value obtained on kraft pulps made with no AQ. This can be interpreted as a result of two opposing effects of AQ: attachment of chromophoric AQ residues to the residual lignin and lessening of lignin condensation. The first effect is expected to become less important as the degree of condensation is lessened, owing to removal of lignin fragments containing the AQ-derived chromophores.

Another significant effect revealed by the regression analysis of the brightness data was a tendency for the optimum final D-stage pH to move upward by about 1 unit (from 4 to 5) as the EA charge in the cook was increased from 16 to 22%. This was accompanied by a brightness increase and may be indicative of a smaller drop in pH during the bleaching of the high-EA pulps.

There was no indication of any negative effect of decreasing unbleached kappa no. on brightness after the D-stage. In fact, there was a small effect in the opposite direction. This may be reconciled with earlier reports of poorer bleachability at low kappa no.[2,12] in either or both of two ways. First, the earlier reports referred to effects on fully bleached brightness, i.e., to bleached pulps with extremely small and presumably similar amounts of lignin present. In such cases, if one pulp contains more highly colored lignin residues than another, substantially more ClO_2 is required to bring it to the same brightness, since chromophore removal becomes increasingly difficult at high brightness values. At lower brightness levels, as in the present study, differences in ease of removal of the more abundant lignin residues may overshadow differences in their color. The second explanation is that effects on bleachability of going to lower kappa number will very probably depend on how the lower kappa no. is attained. For example, prolonging the cook probably has a different effect than increasing the EA charge at constant H-factor. The difficulty arises from the fact that kappa no. is a dependent variable, not an independent one, and its "effects" are meaningful only if the independent variables that were actually changed are specified, together with the constant values of the other ones. In the present work, the kappa no. was changed by increasing the cooking time, whereas Virkola[12] increased the EA charge.

The effects of the experimental variables on brightness reversion of the bleached pulp are displayed in Figure 14. AQ had little effect at charges up to 0.1% and was generally beneficial at higher charges. Lower unbleached kappa no. resulted in a more stable bleached brightness, probably as a result of the retention of less lignin in the bleached pulp. Increased effective alkali is beneficial when cooking to low kappa no. but not when the unbleached kappa no. is in the 30's. The former effect is probably associated with lower hemicellulose contents resulting from the high EA charge, whereas the effect of lignin residues may predominate when the unbleached kappa no. is high.

Bleaching of kraft pulps is usually accompanied by some loss in strength which may, however, be more than compensated for by the attendant increase in the number of fibers per gram of pulp. Zero-span tensile strength is, to a first approximation, a measure of fiber strength if it is corrected to a given yield level and can be used to monitor strength loss during bleaching. Figure 15 shows the results of such measurements on the bleached pulps after correcting to 50% yield. (Bleached yields were not measured but were estimated from the unbleached yields by assuming 0.2% shrinkage for each unit of unbleached kappa no.) The trends are much the same as those shown in Figure 7 for the unbleached pulps, but the general level is slightly lower. Thus, at low kappa no., the gain in zero-span strength associated with AQ addition is preserved through the bleaching sequence. Comparison of the unbleached and bleached zero-span data reveals that the reduction in zero-span strength upon bleaching is linearly related to unbleached kappa no., as shown in Figure 16. This implies that for equivalent bleached pulp strength, the unbleached strength of low-lignin pulps need not be as high as that of conventional pulps. Regression analysis also revealed that the pulps made with high effective alkali charges tended to lose more strength on bleaching.

CONCLUSIONS

1. At a given unbleached kappa no., the effects of the EA level used to prepare a southern pine kraft or kraft-AQ on its subsequent response to CED bleaching are not very great. Over the range 16-19%, higher EA levels give higher unbleached brightness, slightly better brightness development in the D-stage, a slight increase in optimum D-stage pH, improved color stability of the bleached pulps when pulping to low unbleached kappa no. and slightly greater fiber strength loss upon bleaching. Varying the EA charge had no effect on the ease of removal of lignin in the C and E stages, or on the viscosity loss in those stages.

2. Increasing AQ charge over the range 0 to 0.2% while holding the unbleached kappa no. constant is similarly without large effect on the bleach response. It results in slightly lower unbleached brightness, lower permanganate number after the E-stage, marginally increased viscosity loss in the C and E stages, slightly poorer D-stage brightness development at low levels of AQ addition and improved brightness stability at higher levels of AQ addition.

3. Reducing the unbleached kappa no. from 35 to 15 by extending the cooking time in the presence of an adequate EA charge causes no difficulty in removing the residual lignin. This is true for both kraft and kraft-AQ pulps. It increases unbleached brightness, decreases the CE kappa no., and increases brightness stability. Brightness after CED bleaching with a limited amount of ClO_2 is marginally increased, whereas viscosity loss in the C and E stages and zero-span tensile loss across the CED sequence are unaffected.

4. The accelerating effects of EA and AQ on the kraft pulping of southern pine persist to quite low kappa numbers. In absolute terms, the

reductions in H-factor are greater at a kappa no. of 15 than at 35.

5. The zero-span tensile strength of the unbleached pulp decreases with increasing EA charge, decreasing AQ charge and decreasing kappa no. The zero-span loss associated with pulping to lower kappa no. decreases as the AQ charge is increased.

EXPERIMENTAL

Experimental Design

The experimental design was a complete 3 x 4 x 3 factorial with the following factors and levels:

effective alkali charge, % o.d. wood: 16, 19, 22
anthraquinone charge, % o.d. wood: 0, 0.05, 0.10, 0.20
target kappa no.: 15, 25, 35

Pulping and Unbleached Pulp Analysis

Previously chipped southern pine which had been stored in a freezer served as a wood source. Prior to pulping, it was air dried at room temperature and screened in a vibratory screen. Accepts passed through a 0.750-inch screen and were retained on a 0.263-inch screen.

Prior to cooking, the appropriate volumes of NaOH solution, Na_2S solution, and dilution water were transferred to a beaker. A 70.00 g o.d. portion of chips was added and the beaker was placed in a vacuum desiccator, where vacuum was applied and broken over a 5-minute period. The chip-white liquor mixture was then emptied into a 500-mL stainless steel cylinder which served as the cooking bomb. If AQ was called for, the appropriate amount was added at this point.

After loading, the bombs were placed in the rotating rack of an oil bath which had been preheated to 60°C. Heat up to the cooking temperature of 173°C lasted approximately 90 minutes. When the desired H-factor had been reached, the bombs were quickly cooled and opened, and the liquor was drained from the cooked chips. The chips were then diluted to 2 L, defibered in a British disintegrator for 2.5 minutes, and washed in a sintered glass Buchner funnel with deionized water.

Kappa no. determinations were done in duplicate for each pulp sample according to TAPPI Standard T236. Viscosity was determined according to TAPPI Standard T230, zero-span tensile by T231 and brightness by T452. Reverted brightness was measured after heating the brightness tabs for 1 hour at 105°C.

Bleaching

All bleaching was done in sealed polyester bags. The chemical charges and conditions are given in the following table:

	C	E	D
% Cl_2	0.22 (kappa)	0	0
% NaOH	0	0.55 (% Cl_2)	0.4-0.5
% ClO_2	0	0	0.80
Time, minutes	45	90	180
Temperature, °C	ambient	70	70
Consistency, %	3.5	10	10

Chlorine residuals were normally about 2% of the amount applied and ClO_2 residuals were zero. After washing, the bleached pulp was diluted and soured with SO_2 to pH 3.0-3.5.

LITERATURE CITED

1. T. J. McDonough and V. J. Van Drunen, Tappi 63 (11):83(1980).

2. S. Norden and A. Teder, Tappi 62(7):49(1979).

3. N. Hartler, Svensk Papperstid. 83(15):483 (1978).

4. B. Carnö, H. Norrström, and L. A. Ohlsson, Svensk Papperstid. 78(4):127(1975).

5. A. Teder and D. Tormund, Tappi 64(4):138(1981).

6. H. H. Holton, Pulp Paper Can. 78(10):T218 (1977).

7. T. J. Blain, Tappi 63(5):125(1980).

8. R. G. Nayak, S. Maheshwari, S. G. Handigol, P. M. Meshramkar, and U. K. Deb, Indian Pulp and Paper 33(5):17(1979).

9. J. M. MacLeod, B. van Lierop, B. I. Fleming, G. J. Kubes, and H. I. Bolker, 1981 Ekman Days Preprints II:47, Stockholm, Sweden.

10. D. H. Grangaard, Tappi 39:270(1956).

11. S. A. Rydholm. "Pulping processes." Interscience, N.Y. 1965. p. 927.

12. N. E. Virkola, O. Järvelä, and V. Vartianen, Paperi Puu 47:575(1965).

13. H. Makkonen, Paperi Puu 48:437(1967).

TABLE I

UNBLEACHED PULP PROPERTIES

EA, %	AQ, %	Kappa No.	H-factor	Yield, %	Viscosity, cp	Brightness	Zero-span Breaking Length, km
16	0.00	33.5	1661	49.7	32.2	23.1	18.3
19	0.00	33.8	1223	49.1	31.6	24.6	18.2
22	0.00	30.4	985	47.5	28.3	28.9	18.9
16	0.05	35.9	1272	51.0	37.0	25.2	19.3
19	0.05	40.4	879	50.2	35.1	25.9	19.6
22	0.05	45.8	639	50.7	33.6	25.2	18.2
16	0.10	34.1	1289	50.8	34.6	23.6	18.9
19	0.10	32.4	891	49.8	32.2	26.5	18.8
22	0.10	38.5	659	50.3	32.6	26.5	18.0
16	0.20	39.2	934	52.0	37.6	23.3	18.2
19	0.20	33.2	789	50.5	33.8	25.5	19.0
22	0.20	39.9	590	51.4	33.1	25.3	17.9
16	0.00	23.1	2164	47.7	26.4	27.9	19.2
19	0.00	24.3	1440	47.5	24.3	30.0	19.0
22	0.00	19.0	1490	46.3	18.7	29.6	16.9
16	0.05	22.4	2129	48.4	24.5	26.1	17.7
19	0.05	25.6	1182	47.7	25.6	30.1	18.9
22	0.05	34.5	887	49.6	28.0	26.9	17.9
16	0.10	27.3	1609	49.8	29.9	25.0	19.0
19	0.10	22.3	1372	48.4	24.1	27.2	17.6
22	0.10	26.4	903	48.9	26.8	27.9	18.0
16	0.20	29.9	1305	50.8	31.0	23.2	18.4
19	0.20	28.0	1005	50.2	28.9	25.3	18.8
22	0.20	28.7	815	50.4	30.4	26.6	17.5
16	0.00	17.2	3308	46.7	20.5	25.6	16.3
19	0.00	14.1	2789	45.3	14.8	28.8	16.2
22	0.00	13.0	2205	44.7	13.2	31.5	16.3
16	0.05	16.8	3190	46.7	18.9	26.6	16.9
19	0.05	14.3	2593	45.4	14.7	29.1	17.0
22	0.05	13.4	2107	44.8	12.6	31.9	17.0
16	0.10	16.9	2994	47.4	19.4	26.2	17.5
19	0.10	14.2	2495	45.9	15.5	28.7	17.5
22	0.10	13.4	1990	45.3	13.0	31.7	16.7
16	0.20	16.4	2379	48.4	21.7	26.5	18.5
19	0.20	15.5	1660	47.7	19.9	28.5	17.7
22	0.20	16.7	1222	46.8	19.9	30.0	17.2

TABLE II

BLEACHED PULP PROPERTIES

EA, %	AQ, %	Kappa No.	CE Kappa No.	Viscosity, cp	D-stage Exit pH	Brightness	Zero-span Breaking Length, km	Reverted Brightness
16	0.00	33.5	4.0	30.9	3.4	74.7	16.1	68.0
19	0.00	33.8	4.3	29.5	3.6	76.5	17.3	69.9
22	0.00	30.4	4.6	27.7	3.1	71.4	18.6	65.5
16	0.05	35.9	4.8	34.5	3.5	71.8	17.1	65.9
19	0.05	40.4	4.3	33.5	3.5	74.8	18.0	68.5
22	0.05	45.8	5.0	34.6	3.1	66.4	18.2	60.5
16	0.10	34.1	4.3	32.6	4.1	74.6	18.0	68.3
19	0.10	32.4	3.9	31.2	3.8	72.3	17.8	66.4
22	0.10	38.5	4.7	32.4	3.2	67.0	16.9	62.1
16	0.20	39.2	3.4	36.2	3.7	82.5	17.7	76.5
19	0.20	33.2	3.5	32.8	3.3	81.4	17.7	75.7
22	0.20	39.9	4.1	32.9	3.5	75.6	15.7	70.4
16	0.00	23.1	3.6	26.3	4.4	80.4	18.2	
19	0.00	24.3	3.6	23.9	3.7	81.5	17.8	
22	0.00	19.0	4.1	19.2	2.9	67.7	17.1	
16	0.05	22.4	3.8	23.8	4.0	77.4	17.1	
19	0.05	25.6	4.1	24.5	3.7	78.1	17.6	
22	0.05	34.5	4.1	24.8	4.1	77.8	17.7	
16	0.10	27.3	3.7	26.8	3.3	78.0	17.1	
19	0.10	22.3	3.9	22.5	4.2	76.5	17.7	
22	0.10	26.4	4.0	22.7	4.2	79.3	17.3	
16	0.20	29.9	3.7	30.5	3.2	77.7	17.4	
19	0.20	28.0	3.9	25.4	4.1	80.9	17.1	
22	0.20	28.7	3.4	26.2	4.1	80.9	17.2	
16	0.00	17.2	4.0	19.7	4.3	76.1	16.6	70.5
19	0.00	14.1	3.6	14.7	3.6	77.7	15.5	72.3
22	0.00	13.0	3.0	12.2	3.7	81.8	15.8	77.1
16	0.05	16.8	3.8	17.5	3.9	76.3	16.2	71.0
19	0.05	14.3	3.6	13.9	4.6	76.2	16.5	71.3
22	0.05	13.4	3.2	10.8	4.5	80.8	15.9	76.6
16	0.10	16.9	3.9	19.5	3.2	72.9	17.0	67.7
19	0.10	14.2	3.3	15.4	3.2	75.9	16.6	70.9
22	0.10	13.4	3.3	12.4	3.9	81.1	17.1	76.3
16	0.20	16.4	2.7	20.4	3.6	80.0	17.9	74.9
19	0.20	15.5	3.4	19.0	3.8	77.4	17.0	72.5
22	0.20	16.7	4.0	16.7	3.9	82.2	16.8	78.0

TABLE III

REGRESSION EQUATIONS

	Equation	R^2	Std. Error
H-factor	$= 1304 - 791XLNK - 247XAQ - 477XEA + 248XLNK^2 + 155XEA^2 + 289XLNK \cdot XEA + 136XLNK \cdot XAQ + 82XEA \cdot XAQ$	0.98	115
Yield, % o.d. wood	$= 48.7 + 2.0XK + 0.9XAQ - 0.5XEA - 0.3XK^2$	0.98	0.33
Unbleached viscosity, cp	$= 26.6 + 8.0XK + 1.2XAQ - 1.6XEA - 1.64XK^2$	0.98	1.09
Unbleached corr. zero-span, km	$= 17.5 + 1.5XLNK + 0.4XAQ - 0.4XEA - 0.4XLNK \cdot XAQ$	0.89	0.52
Unbleached brightness	$= 27.1 - 1.7XK - 0.6XAQ + 1.7XEA$	0.83	1.04
CE kappa no.	$= 3.8 + 0.3XK - 0.2XAQ - 0.2XAQ \cdot XK$	0.61	0.32
CE viscosity	$= -0.41 + 0.96$ (unbleached viscosity)	0.97	1.24
Viscosity loss in CE stages, cp	$= 1.8 + 0.5XAQ - 0.5XK^2$	0.24	1.12
CED brightness	$= 75.8 - 0.9XK + 3.8XAQ^2 + 4.3XPH + 3.8XAQ^2 - 5.0XPH^2 + 3.9XPHXEA$	0.73	2.38
CED post color no.	$= 2.5 + 0.2XK - 0.4XAQ - 0.1XEA + 0.2XK \cdot XEA - 0.3XAQ \cdot XK - 0.4XAQ^2 + 0.3XK \cdot XEA^2$	0.95	0.21
CED corr. zero span	$= 16.2 + 0.6XLNK + 0.3XAQ - 0.7XLNK^2 - 0.5XLNKXAQ - 0.4XAQ \cdot XEA$	0.77	0.48
Corr. zero span loss in bleaching	$= 1.6 + 0.7XK - 0.2XEA$	0.60	0.58

NOTES

1. The independent variables are defined as follows

$$XK = \frac{\text{kappa no.} - 25}{10}$$

$$XLNK = \ln(\text{kappa no.}) - 3.18$$

$$XAQ = \frac{\text{AQ charge, \%} - 0.1}{0.1}$$

$$XEA = \frac{\text{EA charge, \%} - 19}{3}$$

$$XPH = \frac{\text{D-stage exit pH} - 3.7}{0.9}$$

2. All coefficients are significant at the 95% confidence level with the following 2 exceptions, which were significant at the 90% level: the coefficients of XAQ · XK in the CE kappa no. regression and the coefficient of XK in the CED brightness regression.

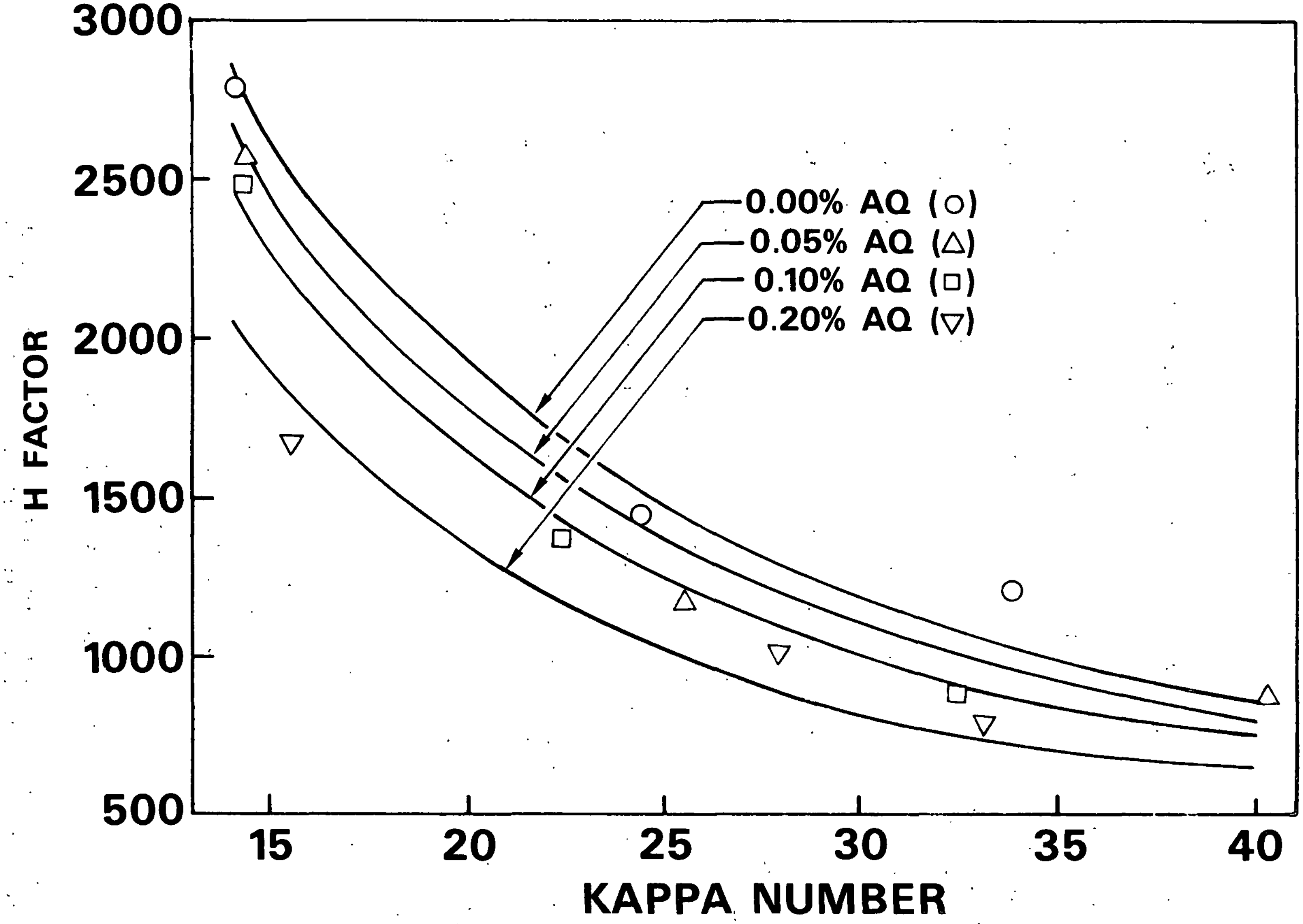

Figure 1. AQ reduces H-factor requirement for larger amounts at lower kappa numbers

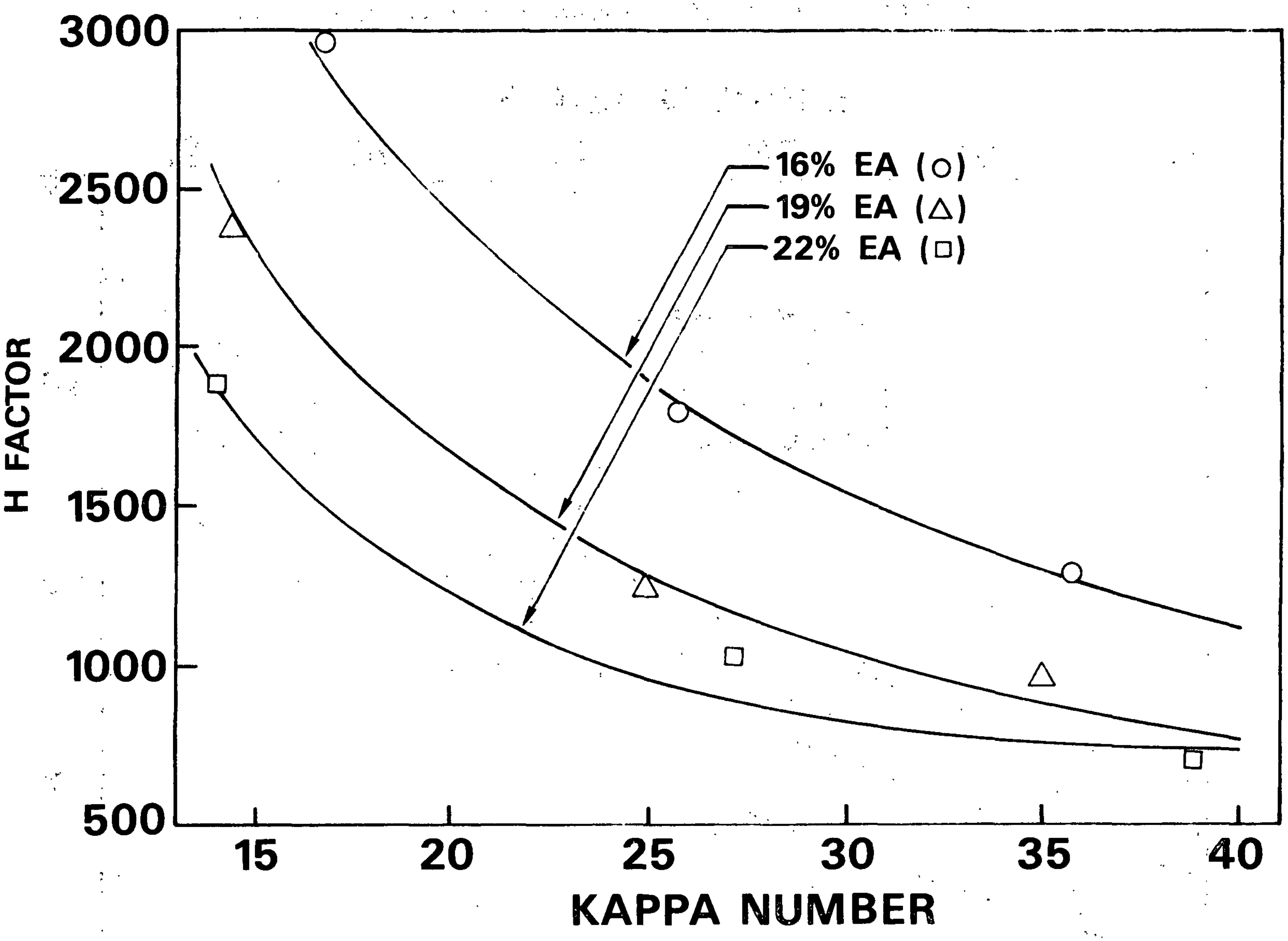

Figure 2. Increasing the EA charge from 16% to 19% reduces the H-factor requirement more than adding 0.2% AQ

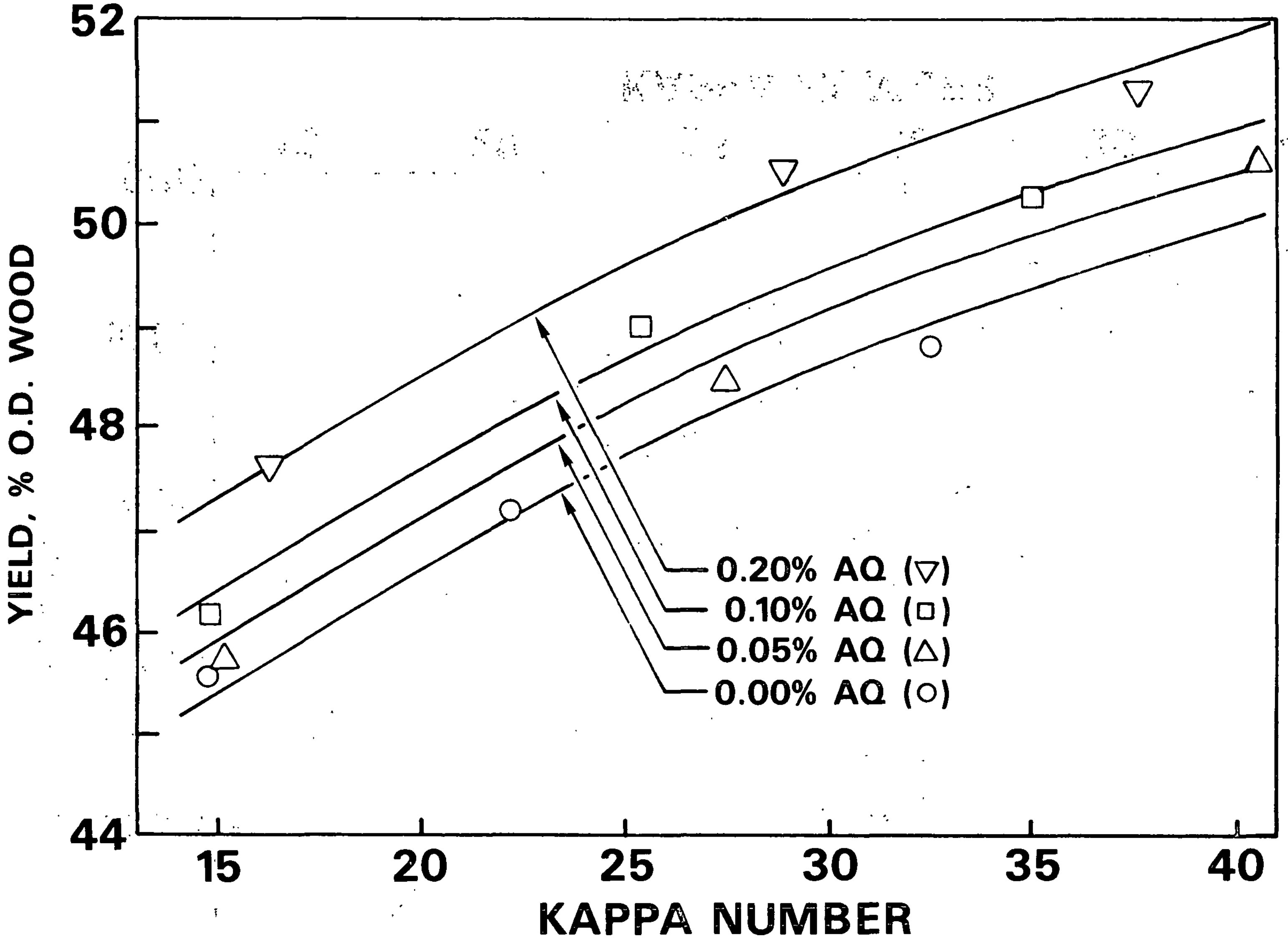

Figure 3. Addition of 0.1% produced a yield gain of about 1%

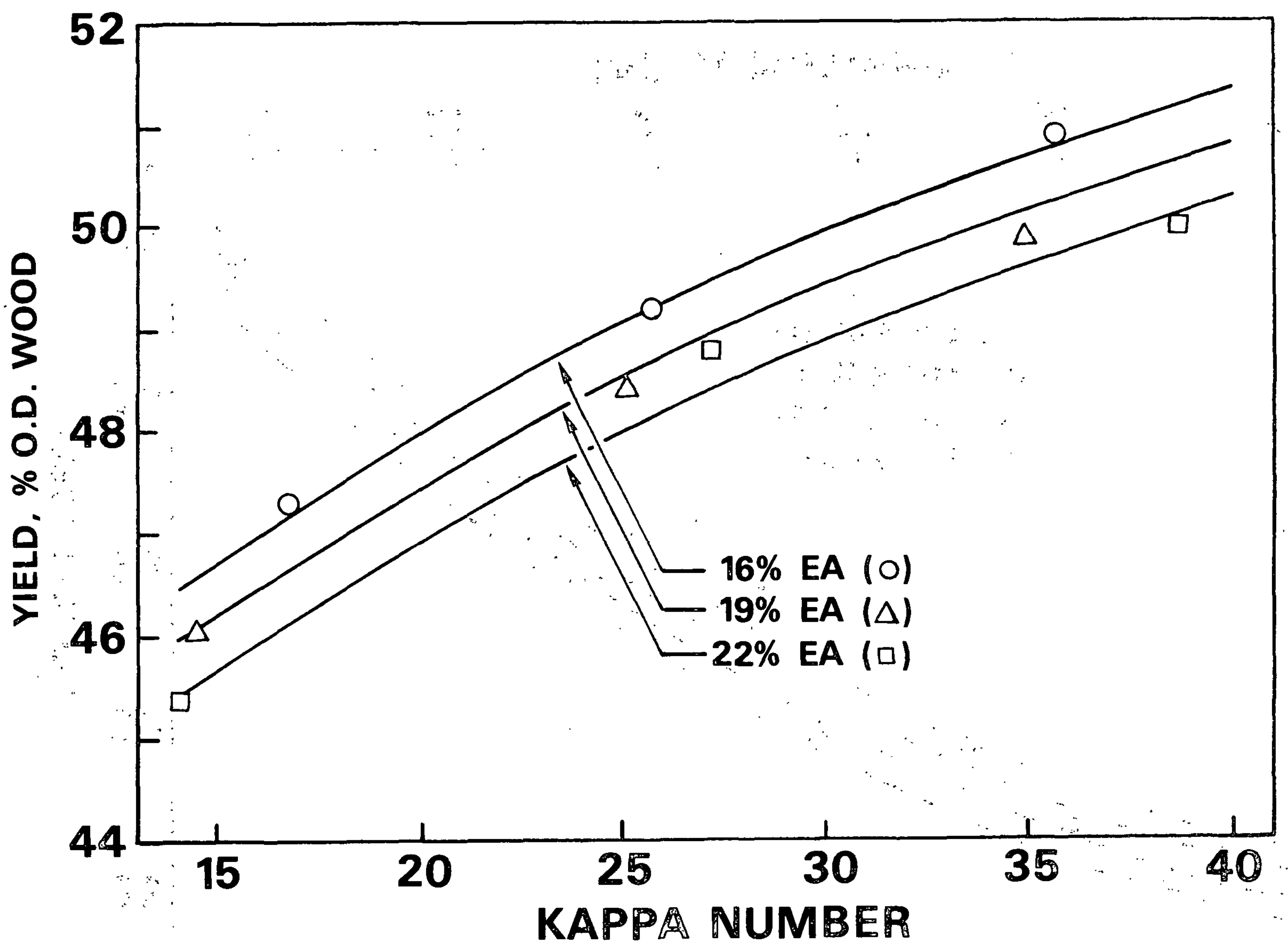

Figure 4. Yield is reduced slightly when higher effective alkali charges are used

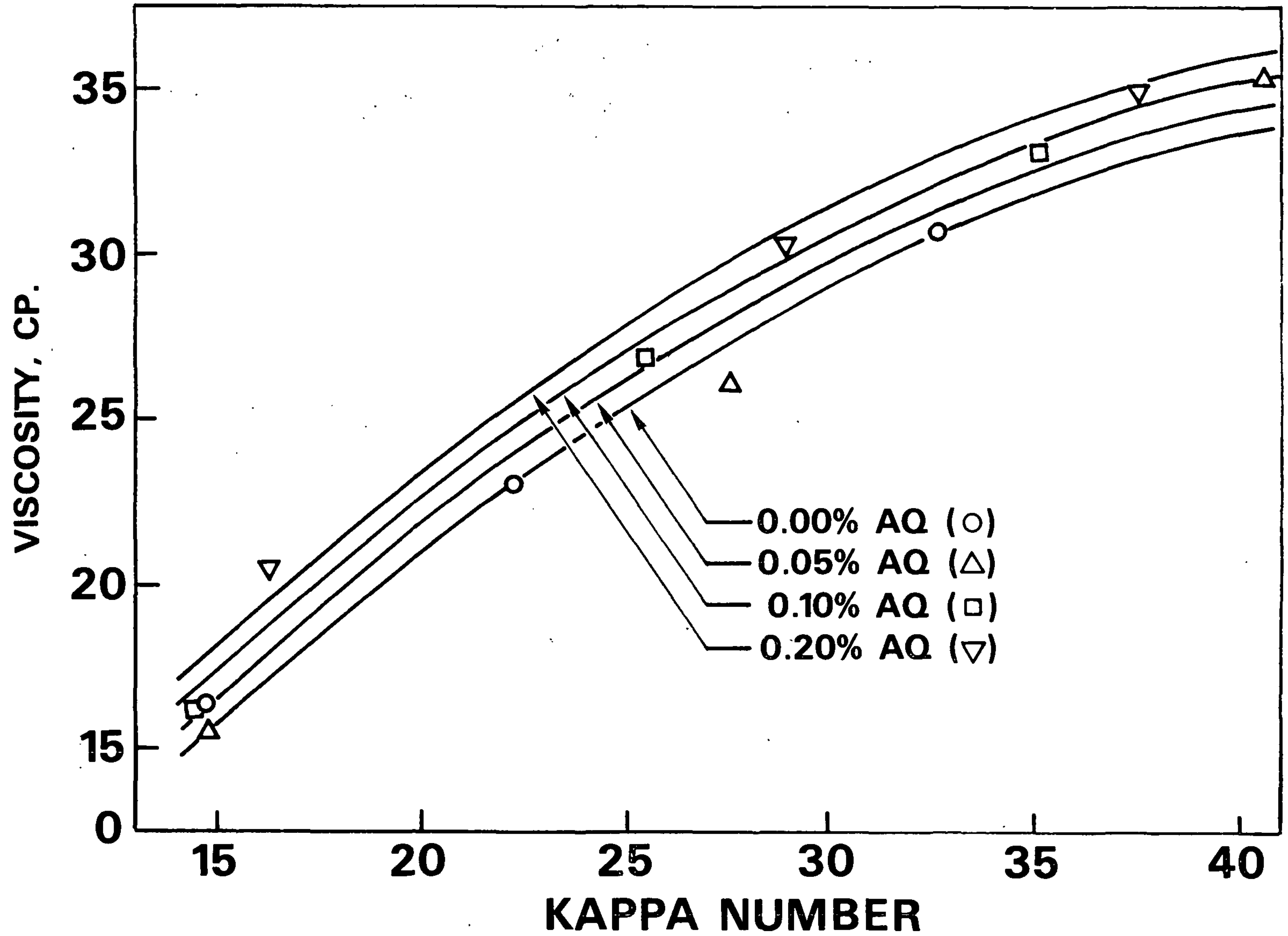

Figure 5. AQ increases pulp viscosity

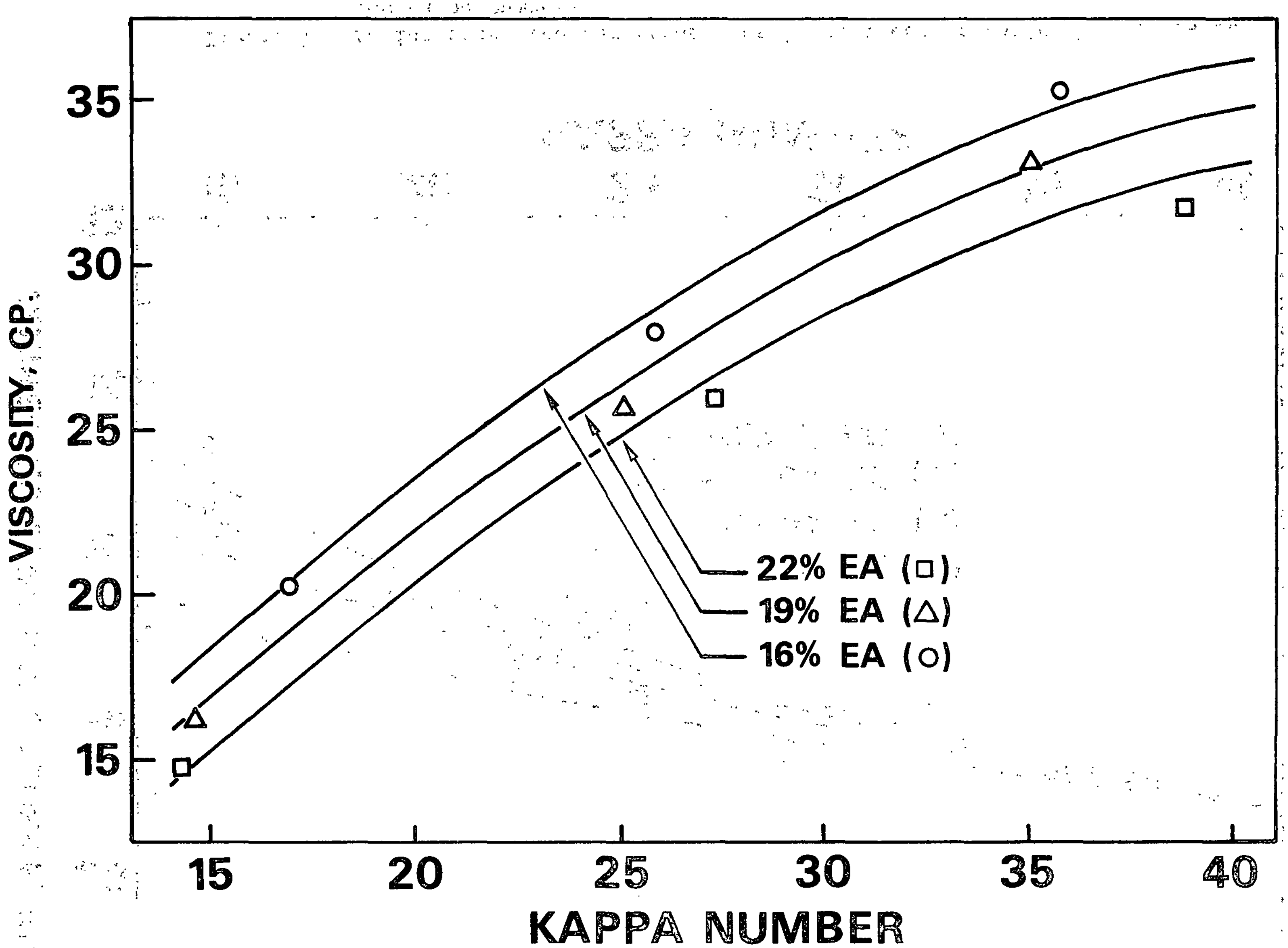

Figure 6. Increasing the EA charge reduces pulp viscosity

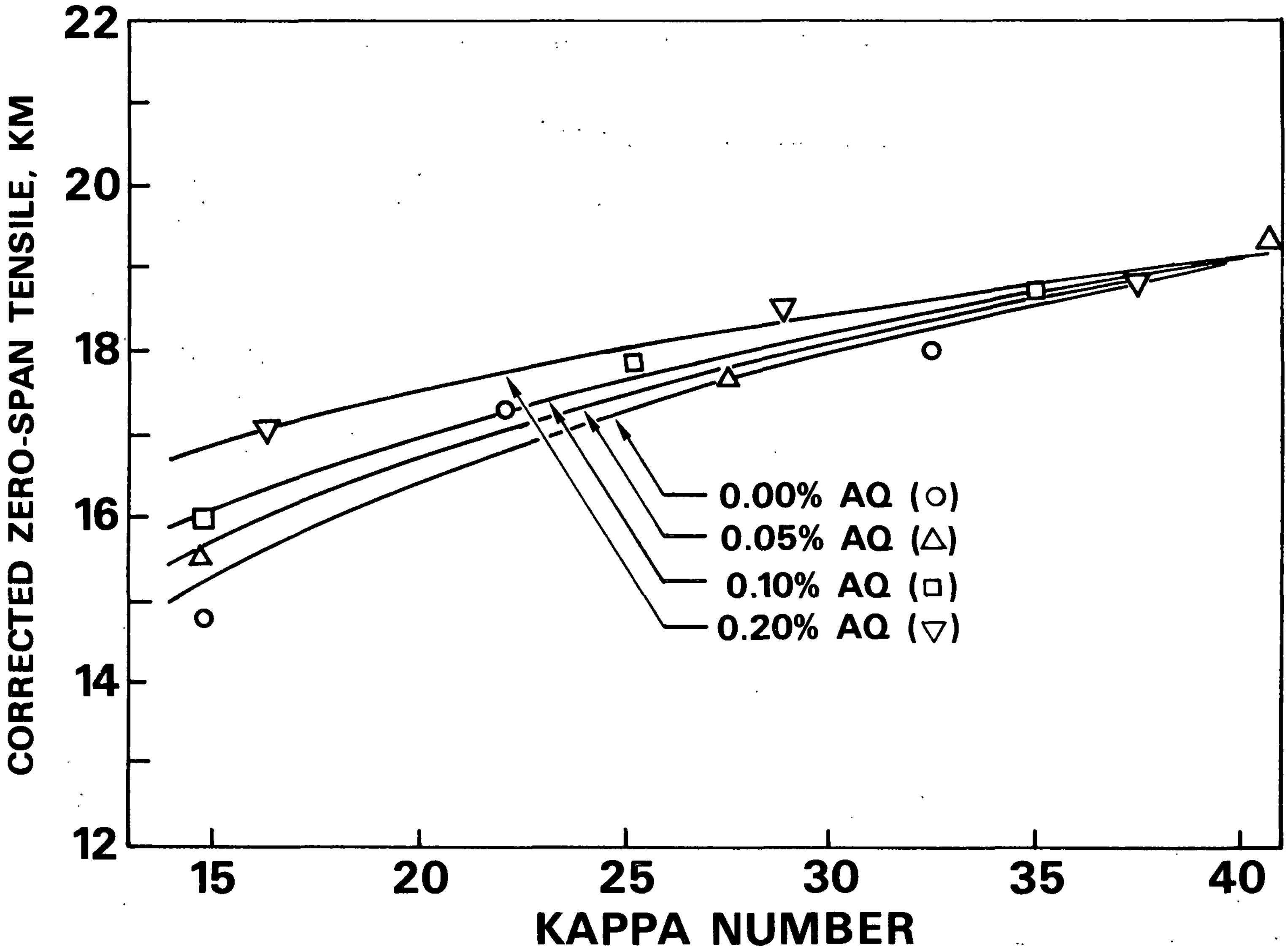

Figure 7. AQ increases the zero-span tensile strength of unbleached pulps at low kappa numbers

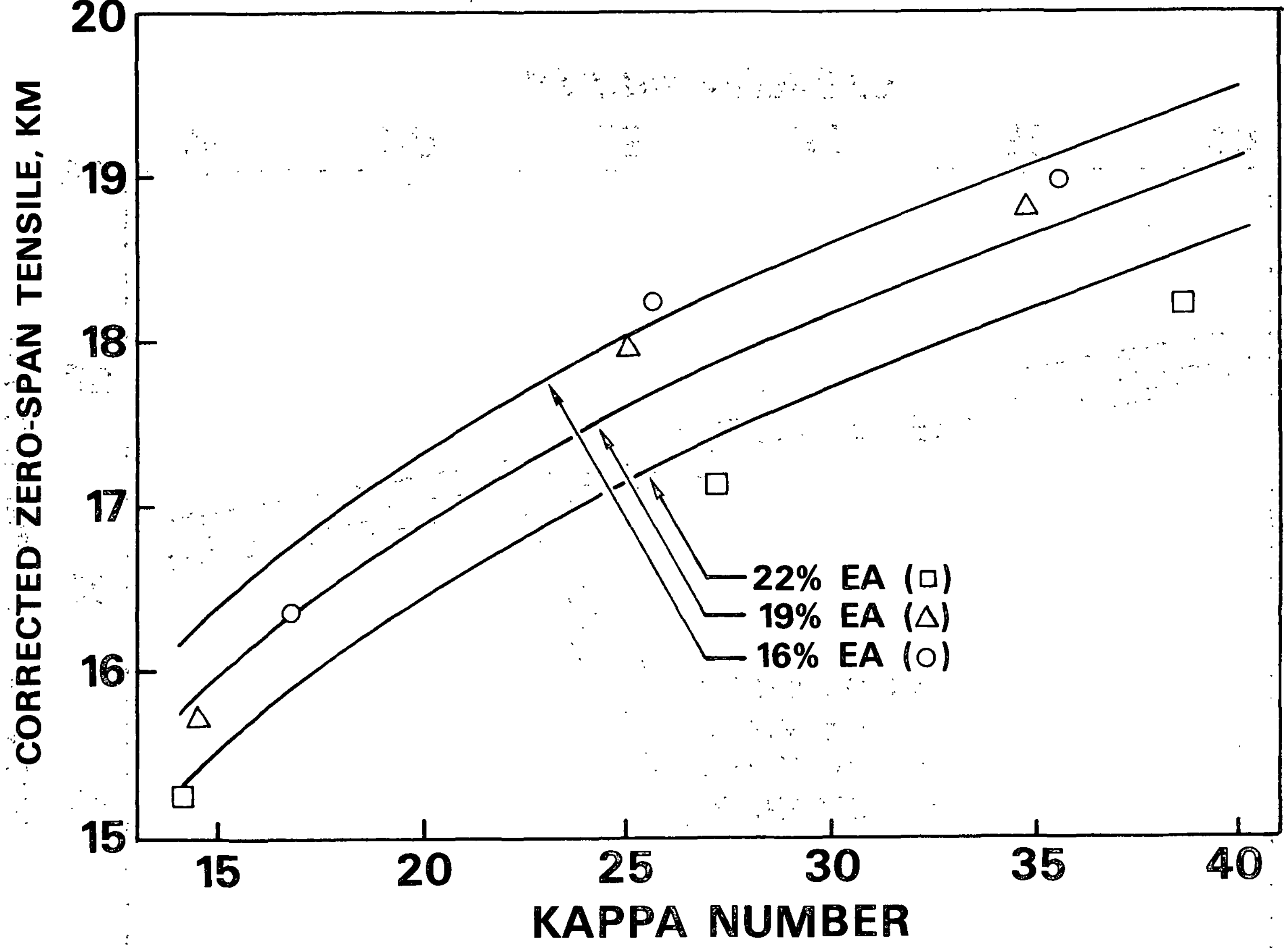

Figure 8. Increasing the EA charge reduces the zero-span tensile strength of unbleached pulps

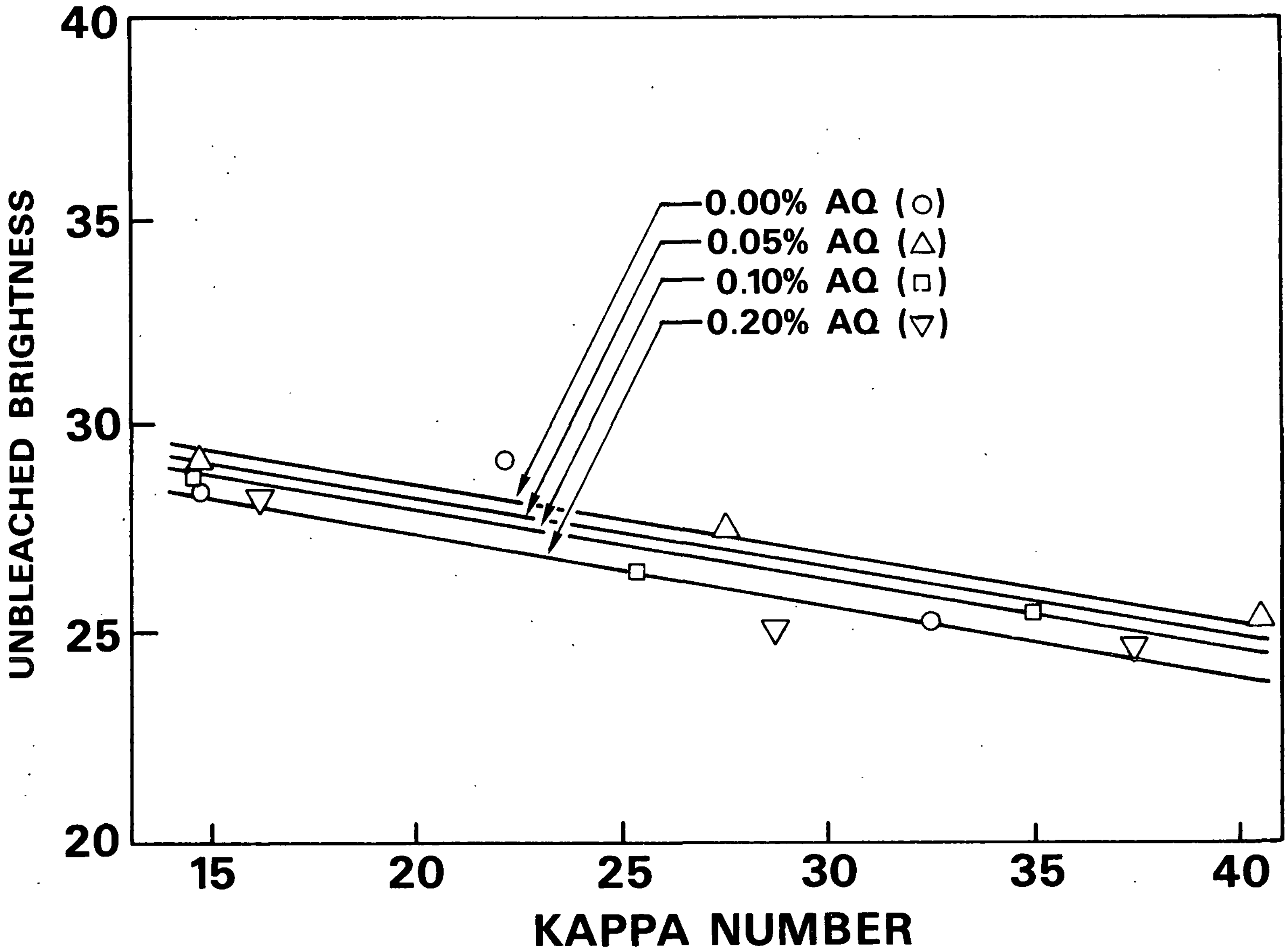

Figure 9. AQ slightly reduces the brightness of the unbleached pulp. Decreasing the kappa no. increases the brightness

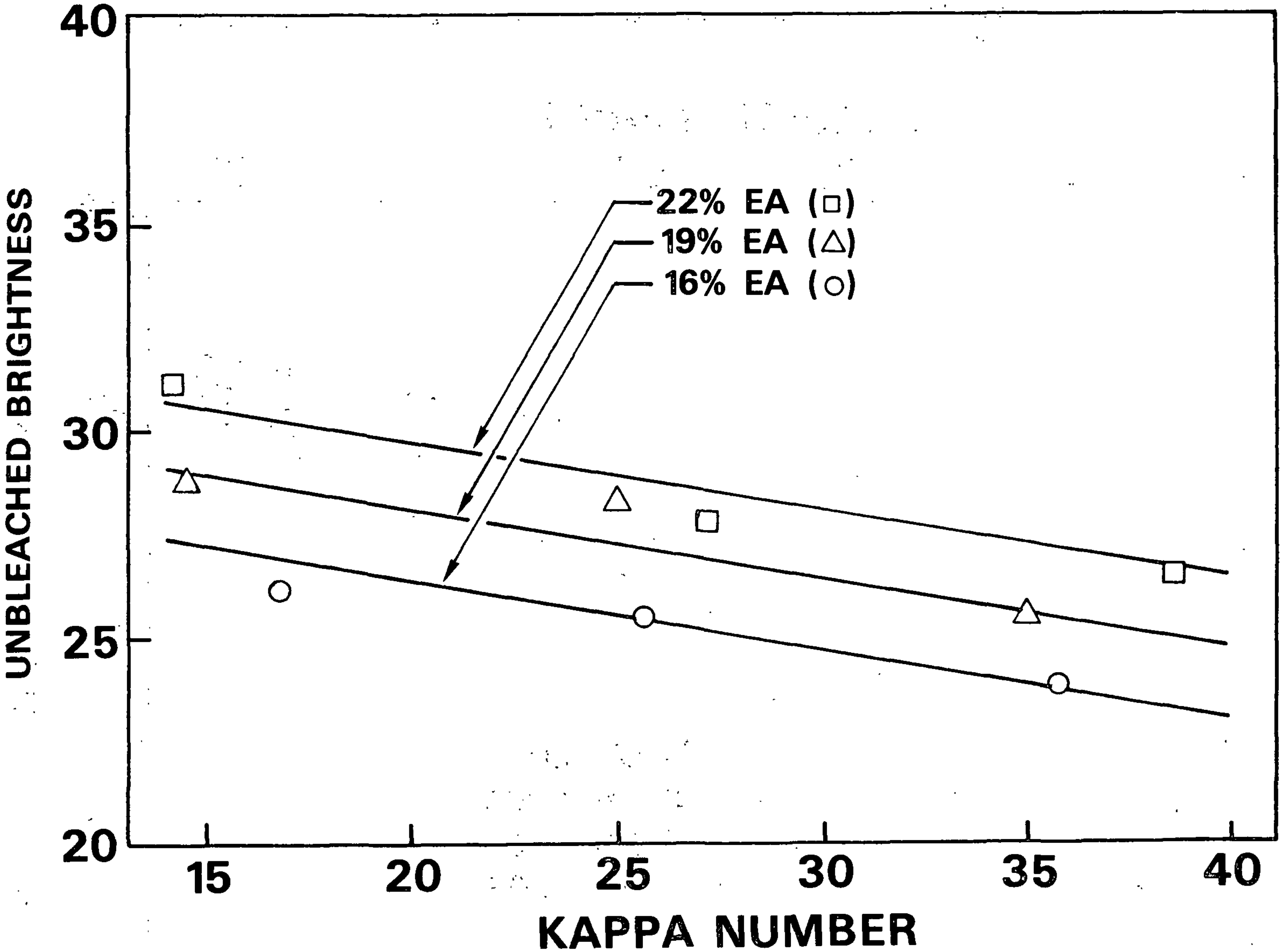

Figure 10. Unbleached brightness increases when the EA charge is increased

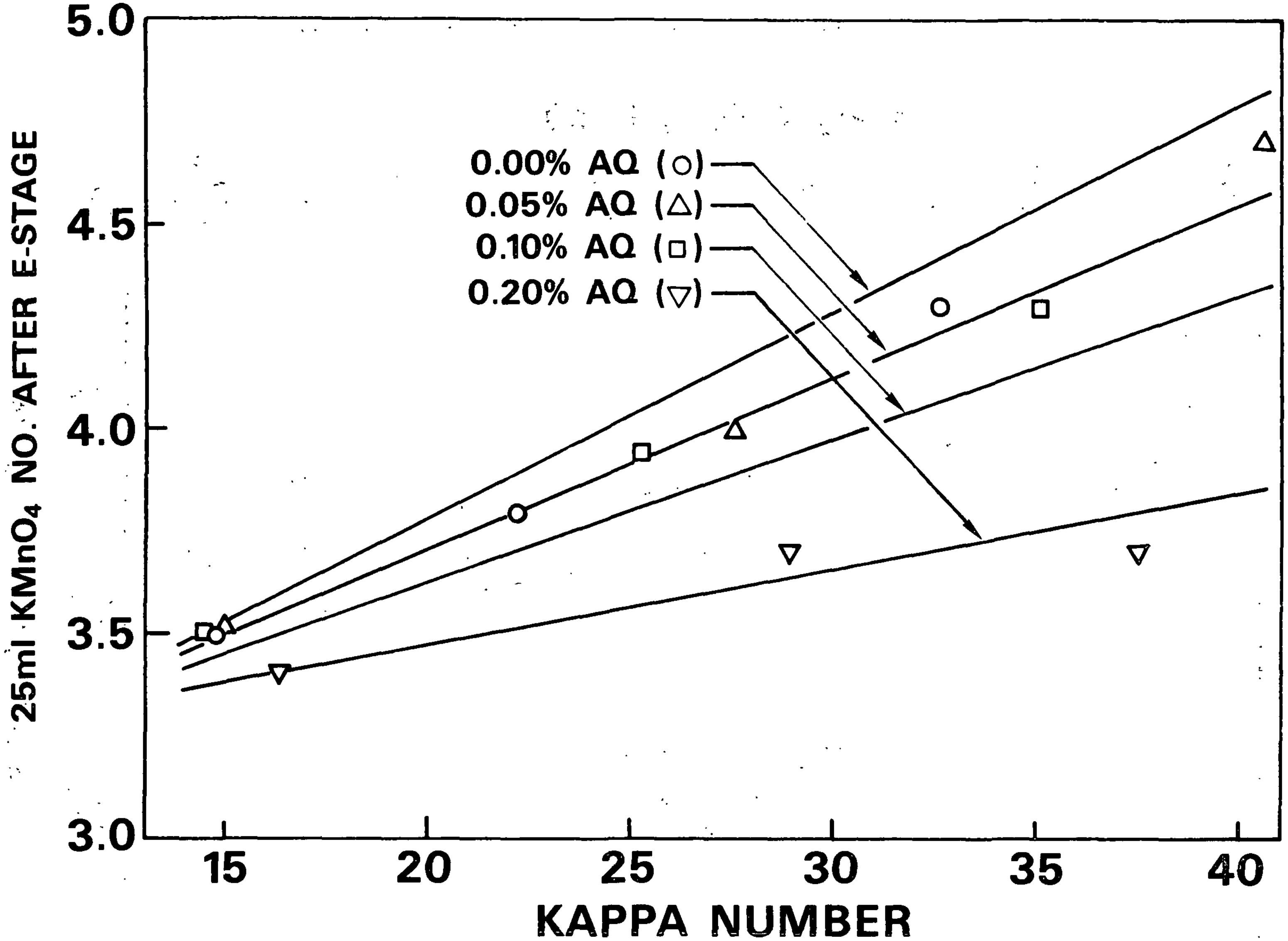

Figure 11. Extracted K no. decreases with decreasing kappa no. and with increasing AQ charge

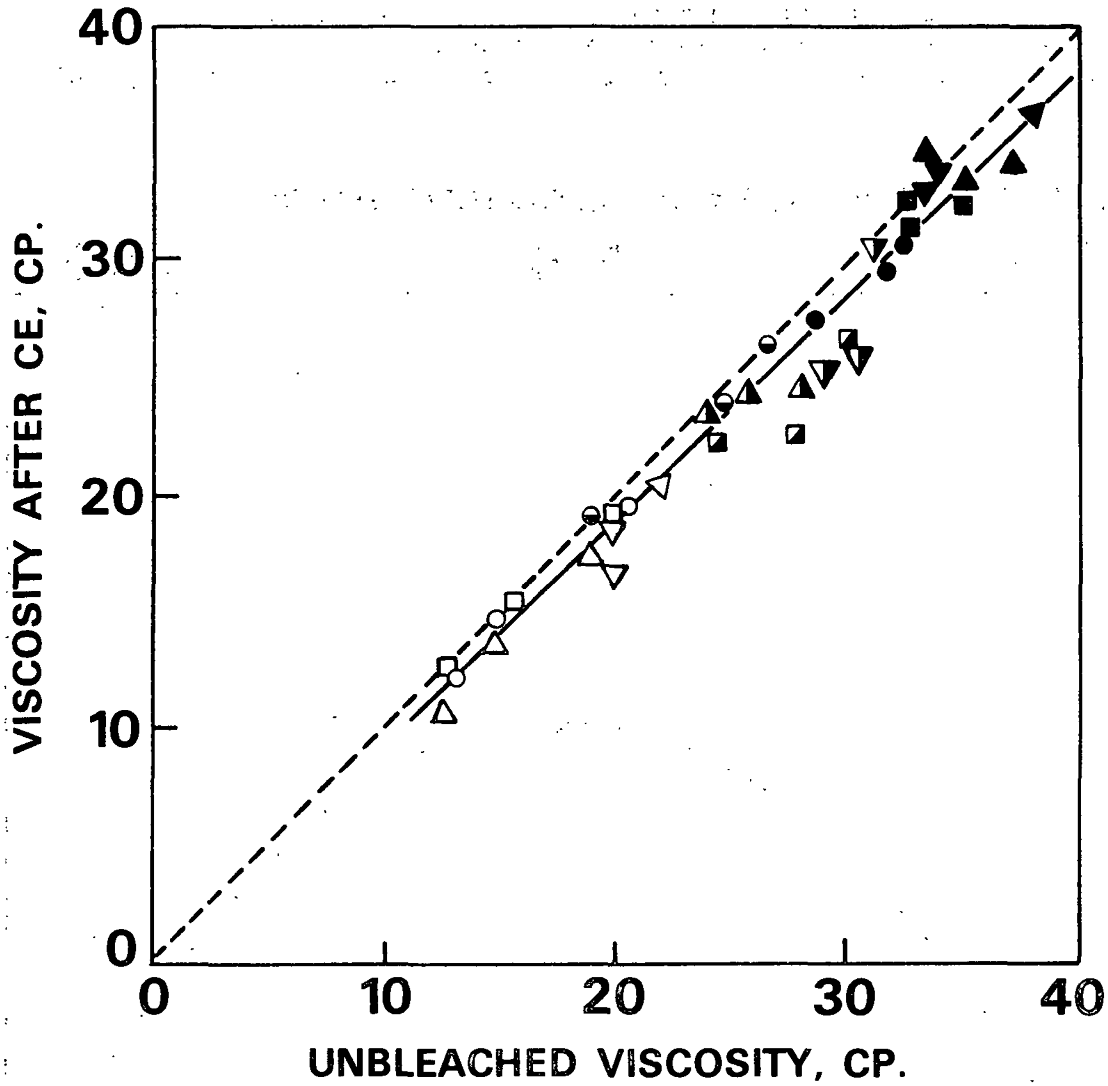

Figure 12. Viscosity losses in the chlorination and caustic extraction stages are relatively unaffected by pulping conditions. Symbols are as follows: Circles, triangles, squares, and inverted triangles denote 0, 0.05, 0.10 and 0.20% AQ respectively. The degree of darkening of the symbols is proportional to kappa no.

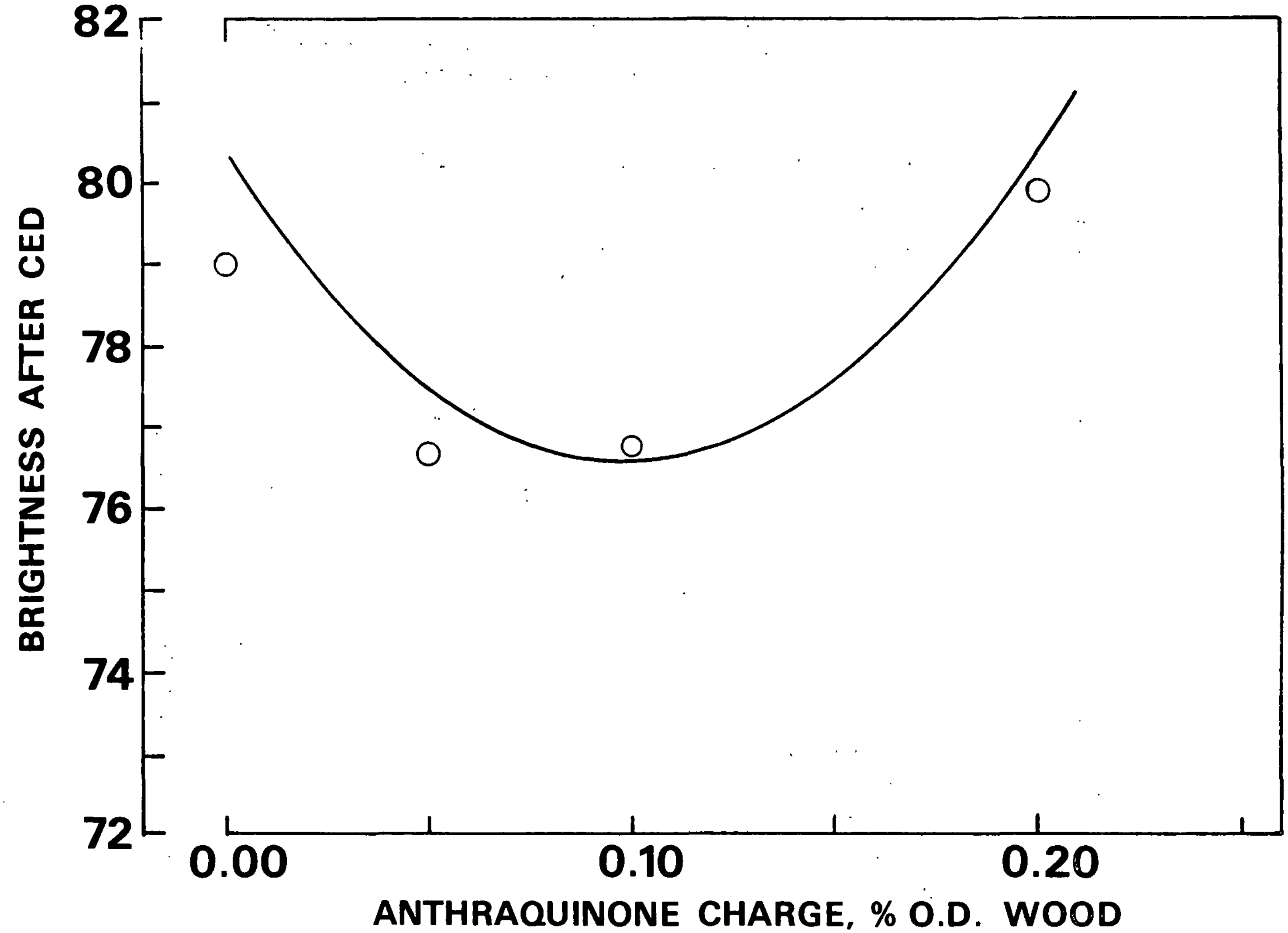

Figure 13. Pulps made with intermediate AQ charges give lower brightnesses. The curve is a plot of the regression equation with pH = 4. The points are averages of all the data, having D-stage exit pH between 3.5 and 4.5

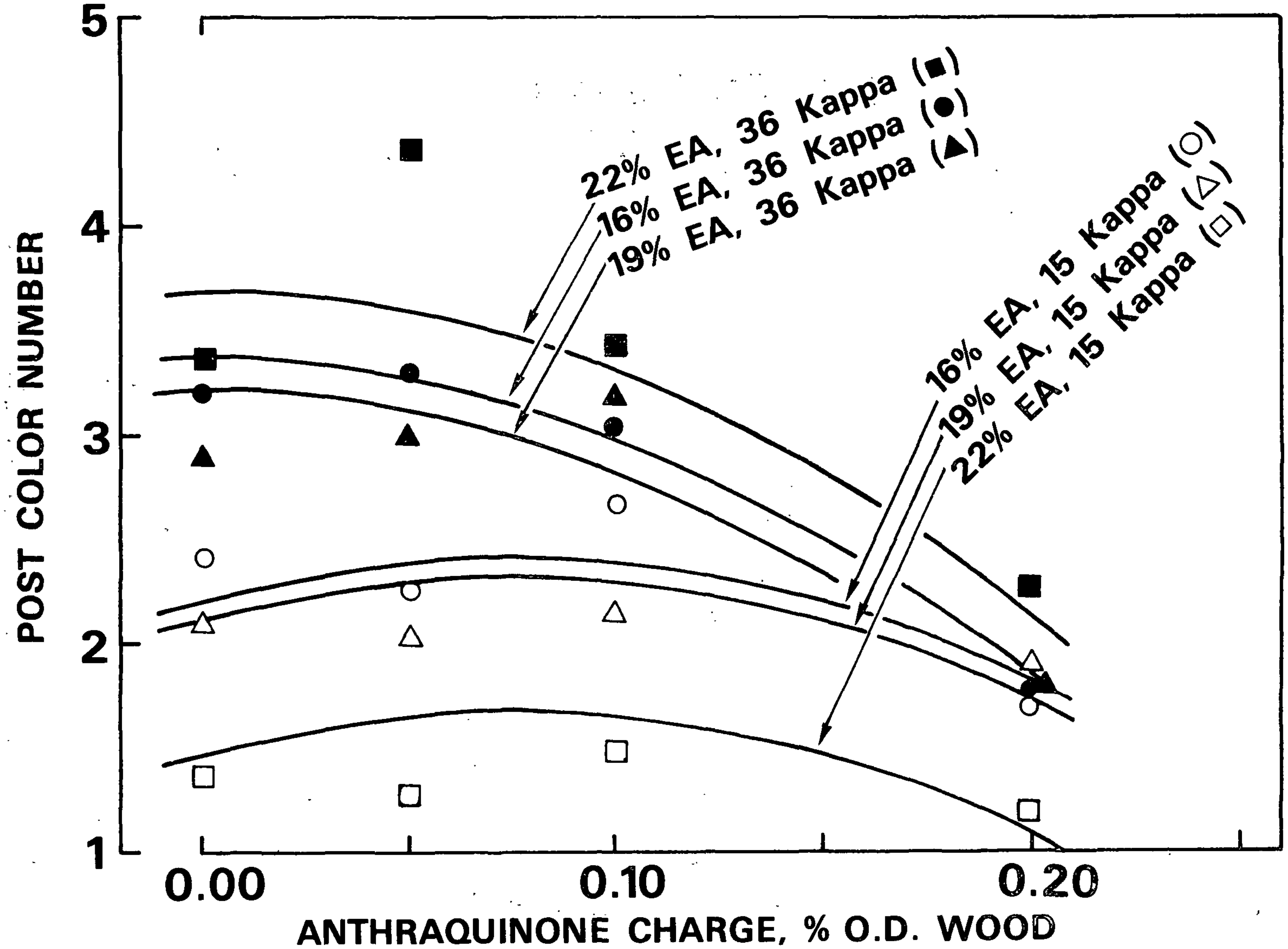

Figure 14. High AQ charges and low unbleached kappa numbers result in improved brightness stability. Increasing the EA charge is beneficial when pulping to low kappa numbers

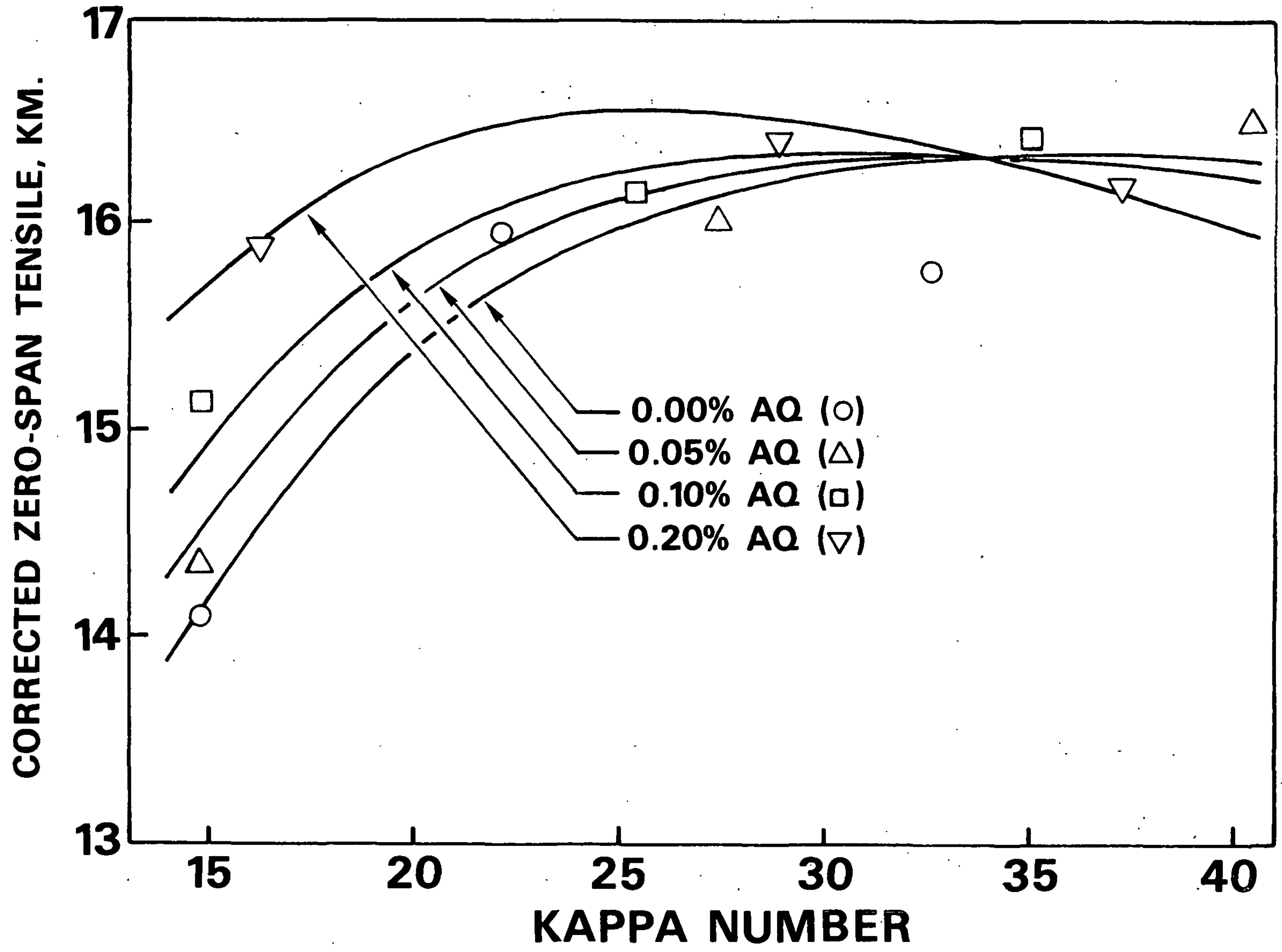

Figure 15. After bleaching, the beneficial effect of AQ on zero-span tensile at low kappa numbers persists

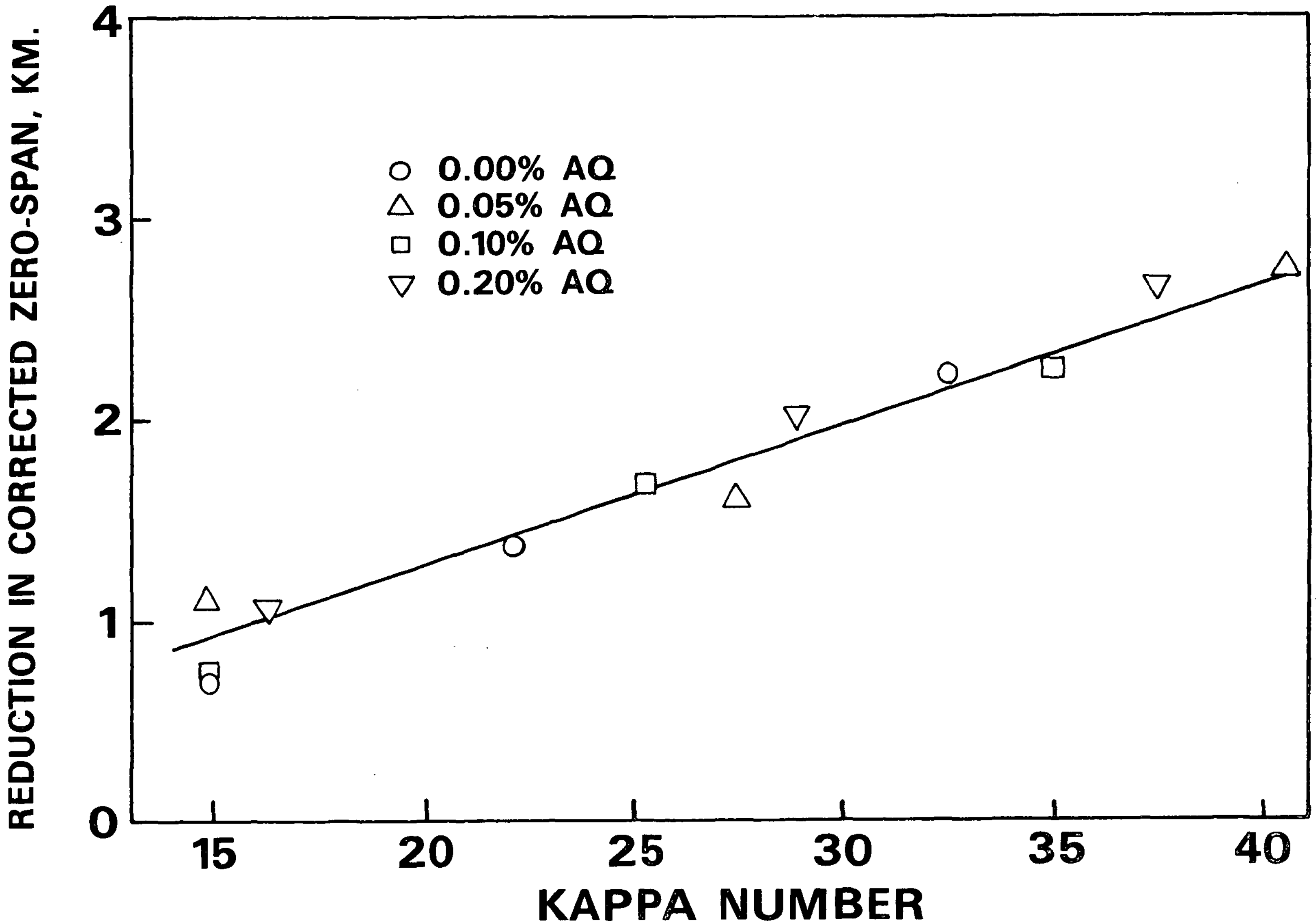

Figure 16. Bleaching reduces the zero-span tensile strength of high-kappa pulps more than that of low-kappa pulps